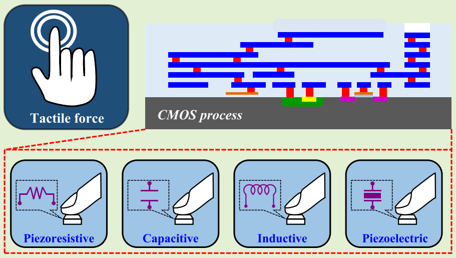
CMOS-Based Tactile Force Sensor: A Review

Sheng-Kai Yeh, Meng-Lin Hsieh, and Weileun Fang, *Fellow, IEEE*

***Abstract*—Tactile sensor is an important medium to receive touching information. The rapid development of the tactile sensor technology was boosted by various application needs and fabrication approaches. Among the applications, force sensing is important in a variety of fields. Several processes including polymer-based, silicon-based, and CMOS-based fabrication techniques have been developed to realize compact, low cost and power consumption, and superiorly performing micro tactile force sensors. Among them, CMOS-based tactile force sensor could leverage the mature semiconductor fabrication technologies and services and is also equipped with the potential of on-chip circuitries with better signal processing capability and quality, which transforms the tactile system into the next level by system on chip (SoC) integration. This article stands on an overall scope of the CMOS-based tactile force sensor to systematically conclude and compare the advanced approaches. The literature on CMOS-based tactile sensor will be reviewed, and process approaches and design concerns of various sensing mechanisms are introduced and discussed.**



***Index Terms*—CMOS, MEMS, tactile sensor, force sensor, piezoresistive, capacitive, inductive, piezoelectric.**

I. INTRODUCTION

VISION, hearing, olfaction, gustation, and tactile perception are five major senses for human. According to the booming of industry 4.0, autonomous car, internet of things, many sensors are required to act as human-machine interfaces [1]. As inspired from the senses of human, the vision, hearing, and tactile perception are considered as promising approaches to serve as the human-machine interface and have been extensively investigated. Comparisons with the human cutaneous touch and use as e-skins have also been discussed extensively in [2]–[6]. The tactile sense is an approach to receive information such as force, temperature, texture, etc. through the contact of object [2], and spatially mapping tactile information can also be sensed by employing tactile sensing arrays as compared with single-point tactile sensing unit [2]–[6]. Presently, the tactile force sensor has been widely used in various fields. Using the robotics application as an example, it is required for nursing care robots to be equipped with tactile force sensors for the dexterous manipulation or collision detection and tactile communication with human [7]. Furthermore, the tactile sensor systems with 3D force sensor in coordinate measuring machine (CMM) system is a typical industry application to monitor the process and quality control during the device fabrication [8]. Also, for medical applications, a force feedback signal could minimize traumatic effects in minimally invasive surgery [9], monitor the loads during the prosthetical treatment [10], and improve medical treatment in orthodontic therapy [11]. Lastly. the tactile sensor could also penetrate into the consumer market as human machine interfaces for entertainment applications [12]. Further information regarding the numerous applications for tactile sensors and details of their measurement specification, price, etc. have been discussed in [6], [13]. In this review article, the force detection function for tactile sensors is the main target unless otherwise specified.

The commercially available conventional force sensors are made by precision-made metal structures with the attachment of strain gauges [14]. Despite their stable performances, the conventional sensors are bulky and costly. Therefore, the approach to integrate the tactile sensor into the target systems for applications is challenging. The silicon or non-silicon based micromachining technologies have been extensively exploited to implement the micro-electro-mechanical systems (MEMS) and find broad applications in the miniaturized sensors and actuators. The MEMS technology paves way for the size as well as cost reduction of the tactile sensor, and MEMS tactile force sensors are commercially available for specific applications [15]–[19]. Moreover, additional benefits taken from the semiconductor materials such as the higher gauge factor from the doping silicon [20] for piezoresistive force sensing, higher initial capacitance and capacitance change from the fine sensing gap defined by MEMS process

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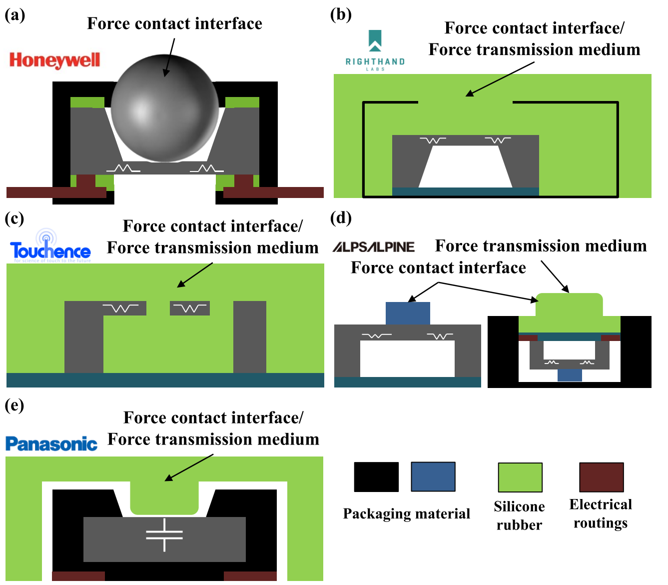

Fig. 1. Schematic illustrations of commercial MEMS tactile force sensors, (a-d) piezoresistive sensing devices [15]–[18] and (e) capacitive sensing device [19].

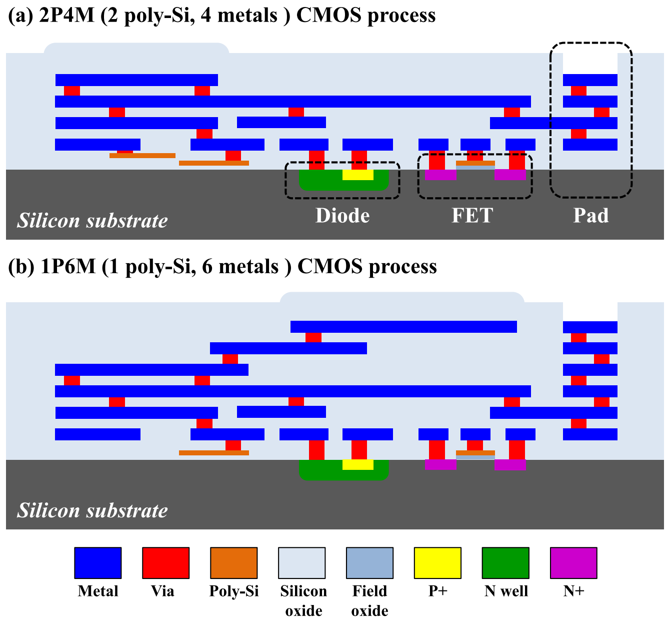

Fig. 2. Typical commercial standard CMOS processes, (a) TSMC 0.35 μm 2P4M CMOS process and (b) TSMC 0.18 μm 1P6M CMOS process.

for capacitive sensing, etc. provide superior performance as compared with non-MEMS fabrication approach. Fig. 1 shows schematic illustrations of five commercial MEMS tactile force sensors, including the piezoresistive sensing devices in Fig. 1a-d [15]–[18], and the capacitive sensing device in Fig. 1e [19]. Various micro deformable structures such as membranes and bridges have been designed for these sensors. The tactile forces could deform the microstructures and further lead the resistance or capacitance changes of the sensors, and hence the applied loads can be detected through electrical sensing signals. Moreover, to properly apply the tactile load on the micro deformable components and also to protect these fragile thin film structures are critical design concerns for these products. In this regard, these commercial tactile force sensors have adopted polymer materials to serve as the force contact interface or force transmission medium, as depicted by the green color in Fig. 1.

To date, various MEMS technologies have also been investigated and developed to design and fabricate micro tactile sensors. For instance, polymer-based fabrication processes have been reported to implement the flexible, stretchable, and large area tactile force sensors [21]–[25]. The silicon-based fabrication processes have successfully been adopted to realize many commercial sensors [26]. Thus, the available design tools and process technologies, and the commercial supply chain and research resources are relatively mature. Many silicon-based tactile sensors fabricated using different processes have been reported [27]–[29]. However, it remains challenging to transfer these silicon-based fabrication processes developed in research institutions to commercial foundries. On the other hand, various standard Complementary Metal-Oxide-Semiconductor (CMOS) processes have been established in many foundries worldwide. It could shorten the development time for commercialization by leveraging these existing CMOS process technologies to develop the MEMS tactile sensors. Moreover, the CMOS process offers various advantages such as on-chip circuitry and device integration, small linewidth definition, multi-layer electrical routings, and so on [30], [31]. Thus, the CMOS-based process technologies are regarded as promising approaches to develop MEMS tactile sensors.

This review will introduce the CMOS-based MEMS processes and their applications for the development of various tactile sensors. Section 2 will focus on detailed discussions of CMOS process platforms and the post-CMOS processes for MEMS sensors and the advantages of using the platform for tactile sensors are emphasized. After that, CMOS-based tactile sensors of different sensing mechanisms, including piezoresistive, capacitive, inductive, and piezoelectric are respectively reviewed in Section 3-6. Distinct CMOS and related post-CMOS processes, sensing mechanisms, mechanical structure designs, tactile force contact interfaces, and force transmission medium are highlighted. Besides, the design concerns regarding the fabrication processes and mechanical structures of sensors are also commented and concluded. Finally, the conclusions and future outlook on the overall scope of CMOS-based tactile sensors are summarized in Section 7.

II. CMOS-BASED MEMS SENSOR

The CMOS process platforms are originally developed for the fabrication of integrated circuits, including microcontroller, microprocessor, digital logic circuit, and so on. Presently, there are various mature and standard CMOS process platforms provided by many commercial foundries. Take TSMC (Taiwan Semiconductor Manufacturing Co., Taiwan) foundry as an example, as shown in Fig. 2, the 0.35 μm 2P4M (two poly-Si and four metal layers) and the 0.18 μm 1P6M (one poly-Si and six metal layers) CMOS platforms are two available standard processes. The CMOS processes, including the front-end-of-line (FEOL) and back-end-of-line (BEOL) processes, typically consist of silicon (with different dopants), polysilicon (with different dopants), metal, and dielectric layers.

Thus, the electronic components such as the transistor, capacitor, resistor, etc., and their electrical connections and outputs are achieved. The rest of the cross-section schematics in this article will follow the color scheme of Fig. 2. From the perspective of sensor development, existing CMOS processes offer the required materials for different sensing mechanisms, for example, the doped silicon and polysilicon with piezoresistivity, the polysilicon with thermoelectric effect, and the metal layers for capacitive sensing electrodes and inductive coil. Thus, various post-CMOS processes such as the etching of metal and dielectric films and the silicon substrate on the CMOS chips have been developed to fabricate the micro sensing devices (CMOS-based MEMS sensors), by which MEMS sensors of piezoresistive [32], thermoelectric [33], capacitive [34], and other sensing approaches have been demonstrated. Moreover, the electronic components available in the CMOS processes can also be exploited to realize sensors, for instance the diode for temperature sensing [35]. Since the CMOS process is mainly used to implement integrated circuits (ICs), it is easy for CMOS-based MEMS sensors to be monolithically fabricated and integrated with microelectronics, hence the sensors or sensing systems can be achieved through the system-on-chip (SoC) approach. In this regard, the CMOS-based MEMS sensor could offer many advantages such as to reduce the electromagnetic interference [36] and the footprint of sensing system [37], to enhance the signal-to-noise (SNR) ratio [38], etc. [30]. In conclusion, the CMOS-based MEMS technology is a promising approach for sensor development and sensing system integration. Presently, many CMOS-based MEMS sensors and sensing hubs have been developed in research organizations as well as in the industry, such as the accelerometer [39], humidity sensor [40], bolometer [41], thermopile based infrared sensor [42], and so on.

Despite the CMOS-based MEMS sensors exhibiting many advantages, some design concerns and limitations resulted from the fabrication processes cannot be ignored. For instance, micro mechanical structures implemented using the CMOS-based processes are composed of metal and dielectric films with process-induced residual stresses. Thus, MEMS structures have unwanted deformations after being suspended from the substrate [43]. Moreover, the metal and dielectric films have different coefficients of thermal expansion (CTE), and hence the MEMS structures will deform due to the temperature variation [44]. Furthermore, some of the functional materials such as the piezoelectric film are not available for the standard CMOS processes [45]. The process compatibility issues such as the thermal budget [46], contamination, and so on, will be critical concerns to deposit new functional materials. In short, to leverage the process technologies of existing CMOS platforms is a convenient approach to fabricate MEMS sensors, however, many design issues need to be considered to implement reliable CMOS-based MEMS sensors. Note that the above design concerns will not be investigated or discussed for articles reviewed in the following sections.

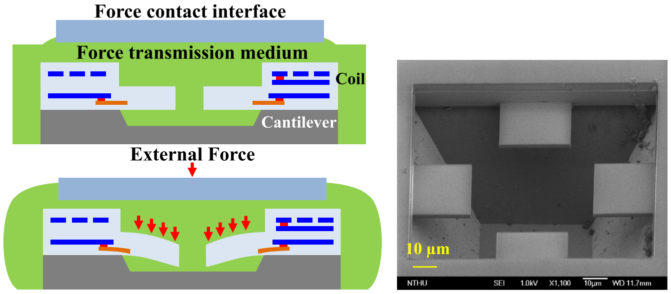

Fig. 3. The schematic illustration and SEM micrograph of the CMOS-based piezoresistive tactile force sensor for normal force detection using cantilevers with poly-Si piezoresistors, and deforming schematic for the cantilever sensing structure (SEM micrograph reprinted from [32], copyright © 2019, IEEE).

III. PIEZORESISTIVE TACTILE FORCE SENSORS

The piezoresistive sensing (strain gauge) is a common approach to detect static and dynamic loads, for example in tire pressure sensors [47] and accelerometers [48]. The piezoresistive materials, such as the doped single crystal silicon and polysilicon, are available for the CMOS processes, as shown in Fig. 2. These functional materials can be exploited to develop the CMOS-based piezo-resistive tactile force sensors [32], [49]–[63]. Similar to most of the piezoresistive MEMS sensors, higher gauge factors can be achieved for these CMOS-based devices through the superior piezoresistive coefficient of single crystal silicon and polysilicon [20]. Nevertheless, piezoresistive sensors are sensitive to temperature changes, and this poses a design concern [64]. In addition to the functional materials, the deformable mechanical structures are required to yield the stress or strain when tactile load is applied. Thus, the stress or strain can be detected by piezoresistors embedded in the deformable structures, so as to further determine the tactile loads. Typically, the dielectric and metal layers for the BEOL of CMOS processes can be employed to fabricate the deformable MEMS structures [65]. In this regard, many different novel structures such as cantilevers, bridges, diaphragms, etc., have been developed to meet the design specifications of various applications. Moreover, as mentioned in Section 1, the real physical contact of force and sensing chip is an occurring concern for tactile sensors. It is of special importance to consider the force contact interface and the force transmission medium as critical design issues. Based on different deformable mechanical structures, this section will introduce various piezoresistive tactile sensors. These tactile sensors are designed and implemented through different CMOS processes. In some cases, the force contact interface and force transmission medium will also be discussed. The SEM micrographs in the following section were selected to show the structural design of the sensor and are not meant to represent the fabricated sensor in final use, that is, the force contact interface and transmission medium are missing in the micrographs. Note that the following literatures will focus on the longitudinal/transverse piezoresistive effect design.

A. Cantilever-Like Structure

The cantilever (a beam with only one end fixed) is a simple mechanical structure which can be easily fabricated using the micromachining processes, and hence finds extensive applications in MEMS devices. Fig. 3 shows a typical example of using the cantilever with embedded poly-Si piezoresistor at the fix end of the beam as sensing elements to detect normal tactile loads [32]. The deforming schematic under

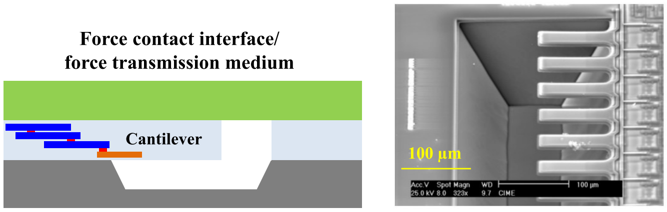

Fig. 4. The schematic illustration and SEM micrograph of the CMOS-based piezoresistive tactile force sensor for fingerprint detection using cantilevers with poly-Si piezoresistors (SEM micrograph reprinted from [49], copyright © 2004, IEEE).

influence of external load for the cantilevers is also shown. The CMOS chip is prepared by the TSMC 0.18 μm 1P6M standard process, and followed up with the etching of sacrificial metal films and tetramethylammonium hydroxide (TMAH) bulk Si etching. This particular CMOS process offered six metal layers. In addition to serving as the sacrificial layers, two metal layers are respectively exploited to fabricate the spiral coil and electrical routings. Thus, the inductive proximity sensor is monolithically integrated with the tactile sensor in the vertical direction. The object can be monitored by this sensor before and after contact. This sensor shows the advantage of the CMOS process for integrating multiple sensing elements. In this study, the chip is encapsulated by polymer after the molding process, and a glass bump is bonded on the polymer. The polymer serves as the buffer layer to transmit tactile load to micro cantilevers (force transmission medium), and also protects fragile suspended cantilevers. Moreover, the glass bump acts as the force contact interface for the tactile sensor.

As shown in Fig. 4, a fingerprint sensor using mechanical cantilever array embedded with polysilicon piezoresistors was presented in [49]. The fingerprint sensor is implemented by the CMOS process (Austriamicrosystems 0.6 μm 3M CMOS process) and the post-CMOS releasing process of TMAH bulk Si etching. A polymer layer is placed on the surface of the sensing chip to act as the protective layer as well as the force contact interface and the force transmission medium. The pattern of fingerprint can be determined by measuring resistance changes of the cantilever array induced by tactile loads from ridges and valleys of the finger. Sweeping of the finger is required to receive the whole pattern of the fingerprint. This study demonstrates the concept of using array type cantilevers to detect the surface profile through tactile contact. The sweeping fingertip speed and the reliability of the cantilever (breakage under higher loads) are two major design concerns. Moreover, algorithms for the detection and scanning of the fingerprint information are required [50].

B. Bridge-Like Structure

The bridge (a beam with both ends fixed) is also a common mechanical structure for MEMS devices. The piezoresistors can be embedded in the two fixed ends of the bridge, and further be employed to form a Wheatstone bridge sensing circuit. Fig. 5 shows an example of using two orthogonal bridges to detect the 3-axis tactile loads [51]. The deforming bridges to detect the 3-axis tactile loads [51]. The deforming schematics under influence of external load for the bridges are also shown. The device is fabricated by the TSMC 0.18 μm 1P6M standard CMOS process, the etching of sacrificial metal films, and the TMAH bulk Si etching. This design takes advantage of the selected CMOS process with 6 available metal and dielectric layers to offer the required structure and sacrificial layers as well as the electrical routings. Thus, the two vertically-integrated bridges and three sets of Wheatstone bridges can be realized. The vertical integration of the bridges can successfully reduce the footprint required to realize tri-axial force sensing. As indicated in Fig. 5, twelve embedded piezoresistors are distributed in the fixed ends of bridges and the silicon substrate to form three sets of Wheatstone bridges to respectively measure the 3-axis tactile loads. The in-plane bending of these two bridges enables the detection of shear forces in two orthogonal directions, and the normal tactile load is detected by the out-of-plane bending of bridge. Finally, this study employs the molded polymer to protect the bridges and also to serve as the force contact interface and the force transmission medium. Fig. 6 displays another example of using bridge-like structures to detect the 3-axis tactile loads [52]. In this study, four sensing elements are distributed in the four corners of the CMOS chip. Each sensing element consists of the bridge-like cross structure with embedded piezoresistors to form the Wheatstone bridge. The in-plane shear loads and the out-of-plane normal loads will cause sensing elements to produce different sets of resistance changes. Based on the relation of resistance changes, the 3-axis tactile loads are extracted. As compared with the vertically-integrated bridges in [51], the design in [52] requires less dielectric layers to form the mechanical structure, and hence the TSMC 0.35 μm 2P4M standard CMOS process is used in this study. Similar to the design in Fig. 3, the spiral

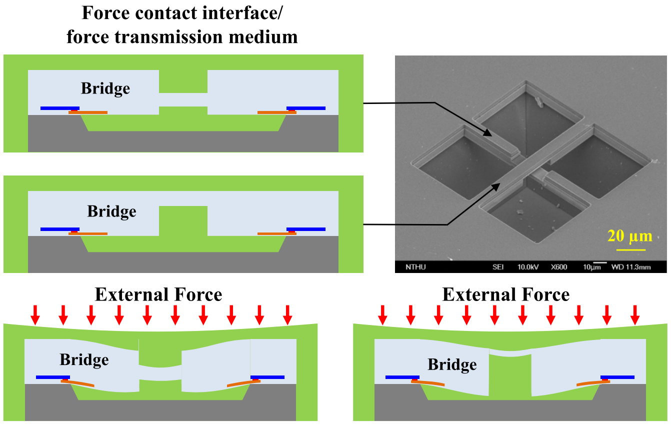

Fig. 5. The schematic illustration and SEM micrograph of the CMOS-based piezoresistive tactile force sensor for tri-axial force detection using bridges with poly-Si piezoresistors, and deforming schematic for bridge sensing structure. (SEM micrograph reprinted from [51], copyright © 2020, IEEE).

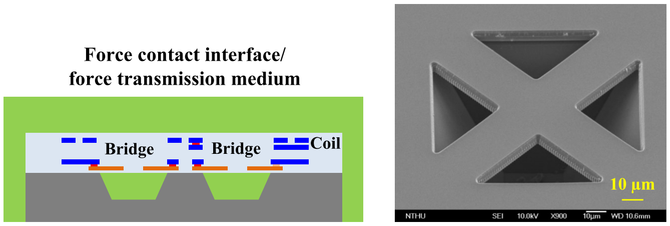

Fig. 6. The schematic illustration and SEM micrograph of the CMOS-based piezoresistive tactile force sensor for tri-axial force detection using bridge-like structures with poly-Si piezoresistors (SEM micrograph reprinted from [52], copyright © 2019, IEEE).

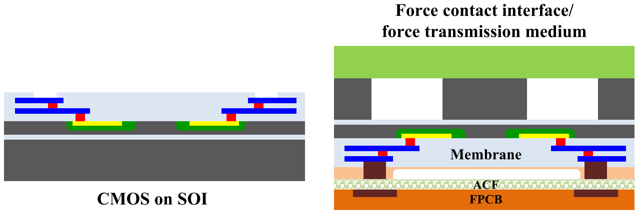

Fig. 7. The schematic illustrations of the CMOS-based piezoresistive tactile force sensor for normal force detection using membrane with doped-Si piezoresistors [53].

coil for proximity sensing can also be integrated in these two 3-axis tactile sensors by using the metal film of CMOS process.

C. Membrane (Diaphragm) Structure

The membrane (diaphragm) structures have been extensively applied in MEMS pressure sensors and microphones. However, since the membrane structure has its boundaries completely fixed, there are several design and process concerns for the CMOS-based tactile sensors such as the complicated warpage due to the release of residual stresses, the etching of sacrificial layer or substrate underneath, the fill-in of polymer protection layer, and so on. As shown in Fig. 7, the CMOS process on the p-type SOI wafer (KEC Corp.) is used to fabricate the normal load tactile sensor with a membrane as the load-deflection structure [53]. After the etching and patterning of the handling substrate of the SOI wafer, the membrane is formed by the suspended device silicon layer and the BEOL metal and dielectric layers. The tactile bump is achieved by the patterned handling substrate, and the piezoresistor is defined by the doped device layer. Finally, the chip is flip bonded on the printed circuit board (PCB) for applications, and the photoresist is patterned as the spacer to define the gap between the deformable membrane and the PCB. Note that the device is covered with silicone rubber as the protection layer as well as the force contact interface and the force transmission medium. This study shows the possibility to use the bulk silicon etching and bonding to form the suspended membrane with piezoresistors on the CMOS chip.

As inspired by the human fingertip, the high density piezoresistors array embedded in a suspended diaphragm on the CMOS chip has been investigated in [54]–[58]. As shown in Fig. 8a, the CMOS process (Toyohashi University) is used to fabricate the piezoresistors and sensing circuits on the device layer of SOI wafer. After flip bonding to a package wafer with cavity and through-via, the handling substrate is patterned and thinned by DRIE to define the diaphragm and the attached pillar array [54]. Another design is displayed in Fig. 8b. In this design, the CMOS chip with piezoresistors and sensing circuits on the SOI wafer is etched from backside (handling substrate) to define the suspended diaphragm. The CMOS chip is then bonded to a package wafer with cavity and through-via, and the SU-8 pillar array is fabricated on the diaphragm by lithography [55]. These designs enable the modulation of diaphragm stiffness and surface profile pneumatically to tune the sensing performances of the tactile sensor and to imitate the 3D surface topology of the human fingertip [56]. Special applications can be achieved through this design at the cost of system complexity. Moreover, the embedded piezoresistors could detect normal loads and their distribution on diaphragm [57]. And by adding the pillar array to act as the force contact interface, the sensing of slippage and in-plane shear force loads can be achieved [58]. In short, the diaphragm structure is needed in these CMOS chips to fulfill the requirement of pneumatic modulation sensing devices. In addition to the tactile force detection, the thermal distribution of contact object can also be measured through the thermometer monolithically integrated with each sensing taxel by the polysilicon of the CMOS process. The signal fluctuation of piezoresistors caused by the temperature variation can also be monitored and compensated.

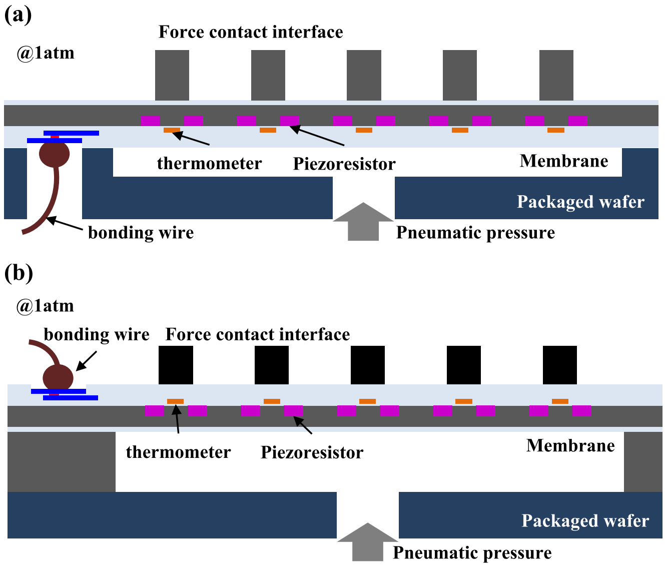

Fig. 8. The schematic illustrations of the CMOS-based piezoresistive tactile force sensors with multi-function tactile load sensing using membrane with doped-Si piezoresistors, (a) design in [54] and (b) design in [55].

D. Hybrid Structure

The vertical integration of two bridge structures in Fig. 5 shows the advantage offered by the multi-layer BEOL of CMOS platform. Fig. 9 further demonstrates the vertical integration of membranes and cantilevers using the TSMC 0.18 μm 1P6M standard CMOS process [59]. Two vertically-integrated membranes are suspended after the sacrificial layers etching, and the cantilever array is suspended after the TMAH bulk silicon etching. The two membrane with metal electrodes forms the capacitive-type force sensing (first stage), and the cantilever array with embedded polysilicon piezoresistors forms the Wheatstone bridge for piezoresistive-type force sensing (second stage). The top membrane will be deformed by tactile load to cause the variation of capacitive sensing gap, and as the load increases, the top membrane will eventually contact the bottom membrane resulting in the deflection of the cantilever array. Thus, the first stage capacitive sensing is used to detect smaller loadings, while the second stage piezoresistive sensing is used to sense larger loadings. However, the mechanical coupling between the first stage and second stage mechanical structures, and the suitable force contact

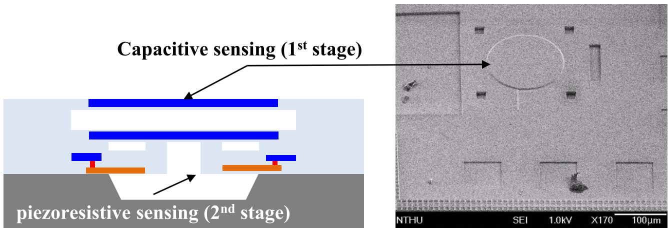

Fig. 9. The schematic illustration and the SEM micrograph of the CMOS-based piezoresistive/capacitive tactile force sensor for normal force detection using hybrid structure with poly-Si piezoresistors and capacitive sensing electrodes (SEM micrograph reprinted from [59], copyright © 2017, IEEE).

interface and force transmission medium should be integrated for future application.

In conclusion, this section reviewed various existing CMOS-based piezoresistive type tactile force sensors. As demonstrated in these articles, various deformable mechanical structures, such as the cantilever, bridge, and membrane, with embedded Si or polysilicon piezoresistors are implemented by different CMOS and post-CMOS processes. As indicated in Section 2, the poly-Si and doped Si layers prepared in the CMOS FEOL processes provide available piezoresistive sensing materials. Moreover, the metal and dielectric layers prepared in the CMOS BEOL processes enable the fabrication of various suspended deformable structures such as cantilever, bridge, membrane, and hybrid structure designs. The patterns of the stacked layers together with different post-CMOS processes have been developed to implement these structures to meet the requirements of applications, and the sensors introduced in this Section are categorized based on the designs of micro mechanical structures. In addition to the thin films of CMOS processes, the polymer and structure for the force transmission medium and force contact interface are also important design concerns for the tactile force sensor, as depicted in Fig. 1. Through the proper combination of piezoresistors, flexible structures, and polymer layer designs, various 1-axis and 3-axis tactile force sensors have been demonstrated [32], [49]–[59]. According to the similar concept, the performances (e.g. force sensitivity, cross-talk between different axes loads, etc.) of CMOS-based tactile force sensors can be further improved by designing the piezoresistors, flexible structures, and polymer layer. Note that the piezoresistor is sensitive to ambient temperature changes. It is convenient to leverage the advantage of CMOS process to monolithically integrate the thermometer with the tactile force sensors on a single chip. The in-situ temperature monitoring of the piezo-resistive tactile force sensor for signal processing and compensation can be achieved. Last but not least, in addition to the longitudinal/transverse piezoresistive effect, the doped Si also has the shear piezoresistive effect which has also been exploited to develop CMOS-based tactile force sensors [60]–[63].

IV. CAPACITIVE

The capacitive sensing is also a mature technology adopted by many commercial products such as the pressure sensor [66], microphone [67], accelerometer [68], and so on. The deformation or displacement of mechanical structures caused by physical loads (pressure, acceleration, etc.) will be detected by the capacitance change of sensing electrodes. Two approaches are frequently exploited to induce the capacitance variation of capacitive tactile force sensors, such as the gap difference between two electrodes (gap-closing effect [24]), and the change of overlapped area between two electrodes (area-change effect [69]). As displayed in Fig. 1, the CMOS process is equipped with the functional material (multilayers of metal) to realize capacitive sensing electrodes and their electrical routings. Moreover, the multiple metal and dielectric layers of CMOS process offer capabilities of superior electrical routing and vertical integration of structures and electrodes. Besides, the monolithic integration of the capacitive sensor with circuit could reduce parasitic capacitance. These are especially important for the capacitive tactile force sensors to form multiple sensing electrodes and their electrical routings for signals input and output. Similar to the approach in Section 3, the dielectric and metal layers for the BEOL of CMOS processes can be employed to fabricate the deformable MEMS structures [65]. However, it is not straightforward to implement the flexible in-plane mechanical structure on the CMOS-based tactile sensors to cause the area-change of sensing electrodes [69]. Presently, the gap-closing sensing based on the out-of-plane deformation of membrane (diaphragm) by normal load is the most common mechanism for the CMOS-based capacitive tactile force sensor [70]–[81]. In this regard, the gap (including size and material) between electrodes can be exploited to change the sensitivity and sensing range of tactile sensors. Thus, the force contact interface and the force transmission medium mentioned in Section 3 remain important design concerns. Two approaches to implement membrane structures with embedded capacitance sensing electrodes on CMOS chip will be discussed in this section.

A. Membrane Through Etching

As shown in Fig. 10 [70], the membrane with embedded sensing electrode is suspended on the CMOS chip (TSMC 0.35 μm 2P4M CMOS process) after removing the sacrificial metal layers. The reference electrode is anchored to the substrate. This step also defines the capacitive sensing gap. Finally, the gap will fill with the polymer to modulate the net stiffness of the tactile force sensor. The out of plane tactile force can be detected by the capacitance change of sensing electrodes after the deformation of the suspended membrane. This design enables the distinct sensitivity and sensing range of the tactile sensor through different fill-in polymers. Thus, the economical, fast, and flexible approach to modulate sensor performances is achieved without changing photo masks. The concept is further extended to develop the tactile sensor with vertically integrated sensing electrodes using the CMOS process with more metal and dielectric layers (TSMC 0.18 μm 1P6M CMOS process) [71]. As shown in Fig. 11, the capacitive tactile sensor consists of two deformable membranes (top and middle membranes) with embedded sensing electrodes and one reference electrode anchored to the substrate. After removing the sacrificial metal layers to suspend the membranes, the CMOS chip is encapsulated by the polymer. The top glass bump is used as the force contact interface and the polymer fill-in between electrodes served as the force

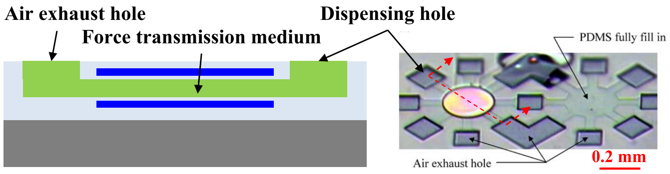

Fig. 10. The schematic illustration and micrograph of the CMOS-based capacitive tactile force sensor for normal force detection using CMOS membrane with polymer filler (micrograph reprinted from [70], copyright © 2011, IEEE).

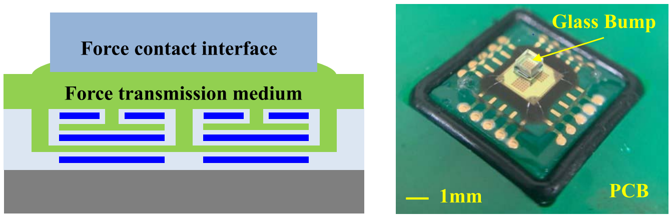

Fig. 11. The schematic illustration and micrograph of the CMOS-based capacitive tactile force sensor for normal force detection using vertically integrated CMOS membranes with polymer filler (micrograph reprinted from [71], copyright © 2019, IEEE).

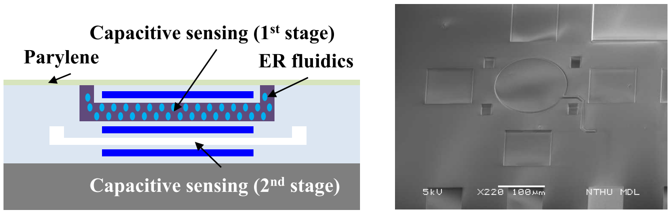

Fig. 12. The schematic illustration and SEM micrograph of the CMOS-based capacitive tactile force sensor for normal force detection using two-stage capacitive sensing design with ER-fluidics filler (SEM micrograph reprinted from [72], copyright © 2015, IEEE).

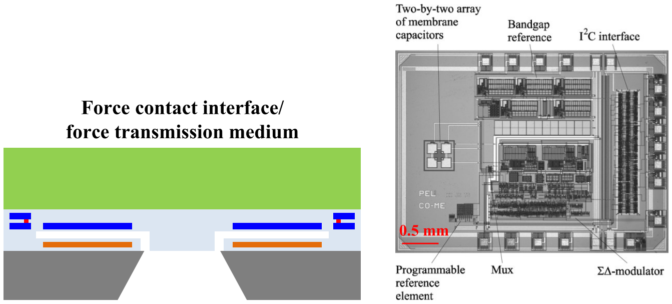

Fig. 13. The schematic illustration and micrograph of the CMOS-based capacitive tactile force sensor for normal force detection using CMOS membrane defined through backside Si etching (micrograph reprinted from [75], copyright © 2007, IEEE).

transmission medium. Thus, the upper and the middle membranes with electrodes can simultaneously deform after loading. These vertically integrated electrodes form two parallel connected capacitors to increase the sensing capacitance, and the footprint of sensing chip remains the same. By leveraging the superior electrical routing capability of CMOS process, the single membrane can be discretize into array membrane to offer the design flexibility.

Moreover, the similar fabrication process (TSMC 0.18 μm 1P6M CMOS) has also been exploited to develop the two-stage capacitive tactile sensor for sensing range enhancement [72]. Fig. 12 depicted the cross section view of the sensing structure composed of three sensing electrodes. The electrorheological (ER) fluid is dispensed and sealed (by parylene) into the upper gap between two deformable membranes with embedded electrodes to act as the first stage capacitive sensing unit, and the bottom gap with no fill-in and its adjacent electrodes to act as the second stage capacitive sensing unit. Similar to the structure in Fig. 9, the smaller normal tactile load deforms the top membrane and sensed by the first stage sensing unit, while the larger force is further transmitted and deforms the middle membrane and sensed by the second stage sensing unit. The enhancement of the sensing range is then achieved. Moreover, the ER fluid can be modulated by electric field to tune the stiffness as well as the characteristics of the first-stage sensing unit. Thus, the in-use modulation of the sensing performances is demonstrated by this CMOS-based sensor. The concept of in-use modulation of the sensing performances for tactile sensor is also achieved in [73]. The chip is fabricated using the similar processes as the one in Fig. 12 except the fill-in material is dielectric PDMS nanocomposite. This design consists of the top loading unit with two driving electrodes, and the bottom sensing unit with two sensing electrodes. Thus the stiffness of the loading unit can be modulated either in-use or in-process by varying the input voltage. Thus, sensitivity and sensing range of the tactile sensor can be modulated.

As reported in [74], [75], the etching of oxide or aluminum sacrificial layers is exploited to fabricate the suspended membrane to realize the capacitive tactile force sensor on the CMOS chip (Austriamicrosystems 0.8 μm 2P2M CMOS process). Fig. 13 shows the cross-sections of sensors respectively defined through the removal of oxide or aluminum sacrificial layers after the bulk silicon micromachining. Note that the backside cavity on the silicon substrate was patterned by KOH to suspend the BEOL layers to define the membrane. The CMOS-based tactile sensor shows novel application for extravascular blood pressure monitoring [75], as shown in Fig. 13. The CMOS chip composed of 2 × 2 capacitive membranes and the peripheral circuits is displayed in this micrograph. In this application, the thick polymer was used as the force contact interface as well as force transmission medium of the tactile sensor to ensure the effective contact and force transmission. The proposed tactile sensor can be used to measure the amplitude of blood pressure, as well as extract the frequency of the extravascular pulse. The measurement results of both were demonstrated to show the fluctuations of the hemodynamic circulation, namely the effect of intrathoracic pressure on blood pressure, and the heartrate difference due to the vagus nerve stimuli on the SA node.

The concept of TI DMD has been adopted in [76] to fabricate dense deformable membrane array (57334 total taxels over 11.2mm×12.8mm array area) on top of the CMOS chip for fingerprint detection. In this application, each taxel is a capacitance sensing element. As shown in Fig. 14a, the post-CMOS surface micromachining is employed to fabricate the protrusions (tactile bumps), suspended membrane array, and sensing electrodes on top of a CMOS chip (prepared by the Nippon Telegraph and Telephone Corp (NTT) using the 0.5 μm CMOS process). A special STP (spin-coating film transfer and hot-pressing) process is used to seal the sensing

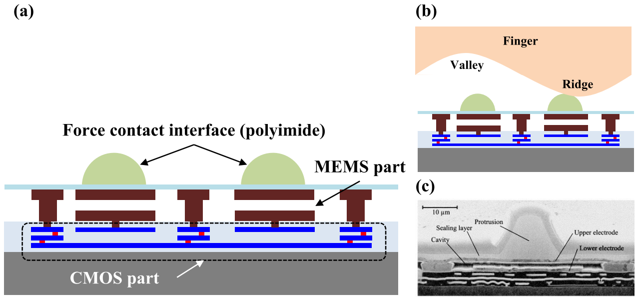

Fig. 14. (a-b) The schematic illustration and (c) SEM micrograph of the CMOS-based capacitive tactile force sensor for fingerprint sensor using CMOS membrane array (SEM micrograph reprinted from [76], copyright © 2003, IEEE).

electrodes of all taxels [82], thereby the concerns of water and other contaminations during fingerprint sensing can be avoided. Note the post-CMOS processes meet the thermal budget requirement of CMOS chip. Fig. 14b also indicates the scheme of fingerprint sensing. The ridges (valleys) on the fingertip will (will not) deform the membrane of each sensing taxel, and hence the fingerprint image can be determined through the sensing capacitances distribution of the membrane array. The typical fabricated fingerprint sensor with MEMS structure on top of the CMOS chip is shown in Fig. 14c. The protrusion defined by the polyimide was the force contact interface of each taxel.

B. Membrane Through Bonding

In addition to the single chip approach discussed above, the two chips solution is also available to realize the tactile force sensor on the CMOS chip. In this regard, the CMOS chip and an additional auxiliary chip can be separately fabricated and then integrated through bonding to offer the process and material flexibility [77], [80], [81]. As shown in Fig. 15a, the CMOS chip (TSMC 0.18 μm 1P6M CMOS) undergoes in-house post-CMOS backside silicon substrate etching (by TMAH) to fabricate the boss as the force contact interface and meanwhile the thickness of the deformable membrane (consisting of silicon substrate and the BEOL layers) for the tactile sensor is also defined [77]. Moreover, the auxiliary chip with reference sensing electrodes and electrical interconnection on the low temperature cofired ceramic (LTCC) substrate is fabricated, and the Au layers are prepared and patterned on both chips (also in-house process). Finally, the CMOS chip is flip-chip bonded on the LTCC substrate using the Au-Au bonding (thermal compression at 180°C). The bonding temperature is lower than the thermal budget of CMOS chip, and the LTCC substrate is selected for the matching of thermal expansion coefficient with silicon [83]. The gap of the sensing electrodes is defined by the height of the Au bump. Note that under this architecture, the boss, suspended membrane, and the sensing electrodes can be designed to meet the specifications of multi-axes forces sensing [78]. More flexible designs on the shape of boss and membrane can be defined by the DRIE, and other sensing components such as the diode-based thermometer can also be added onto the CMOS chip [79].

On the other hand, as shown in Fig. 15b, the deformable membrane with sensing electrode is fabricated on the auxiliary chip using the double side bulk micromachining on silicon substrate [80]. Thus, the flexible membrane, the sensing gap, and the boss for force contact interface are defined after the TMAH wet etching. In this case, the CMOS chip is only used to provide the sensing circuits. The benzocyclobutene (BCB), with high chemical and thermal stability, small outgassing and low permittivity [84], is selected as the adhesive bonding layer. However, special treatments on the BCB layer are required. By extending the concept in Fig. 15b, Fig. 15c shows the implementation of deformable membrane, boss, and sensing electrode on the auxiliary chip using the micromachining on SOI wafer [81]. The boss and membrane are defined on the handling substrate of SOI wafer using the DRIE, and the sensing electrodes are patterned on the device layer. The process on SOI wafer offers the design flexibility for realizing suspended electrodes supported by torsional springs. Thus, novel sensing mechanism is achieved through these electrodes. Note that special requirements on the electrical interconnection and routings such as the TSV are needed for the tactile force sensors using membrane through bonding designs.

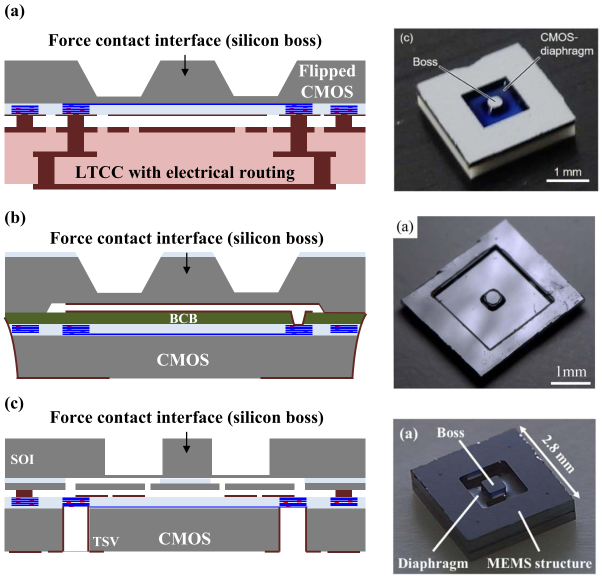

Fig. 15. Schematic illustrations and micrographs of the CMOS-based capacitive tactile force sensors, (a) normal force detection design using bonded capacitive membrane (micrograph reprinted from [77], copyright © 2016, Elsevier), (b) tri-axial force detection design using bonded capacitive membrane (micrograph reprinted from [80], copyright © 2012, Elsevier), and (c) tri-axial force detection design using bonded capacitive membrane (micrograph reprinted from [81], copyright © 2018, Elsevier).

In conclusion, this section reviews CMOS-based capacitive tactile sensors fabricated using various CMOS and post-CMOS processes. Based on the formation of deformable structure (membrane) for these sensors, the discussions are categorized as the single chip solution (membrane through etching) and the two chips solution (membrane through bonding). Similar to the approaches in Section 3, the suspended MEMS structures are mainly formed by the metal and dielectric layers of CMOS BEOL after the post-CMOS release for the single chip solution. The single chip solution could leverage advantages of the CMOS process to offer sub-micron sensing gaps and multiple metal-layers electrical routings for capacitance sensing electrodes. Thus, the design and integration of sensing electrodes are relatively flexible and the sensing signal can be improved accordingly. Moreover, the polymer filler between sensing electrodes could further be exploited to modulate the characteristics of tactile sensors. Through this approach, the re-design and change of photo masks are not required which can save development time and cost. It is worth noting that, to enhance the capacitance signal, a smaller gap between sensing electrodes is preferred. In this regard, the residual stresses and CTE mismatch for the metal and dielectric layers of CMOS BEOL will cause unwanted deformations of the suspended MEMS structures and further change the performances of the sensors. On the other hand, for the two chips solution, the suspended MEMS structures are formed through the wafer bonding. Thus, there are more choices for the materials to fabricate the suspended MEMS structures. The influence of residual stresses and CTE mismatch for the thin film layers of CMOS BEOL can be avoided. However, some concerns such as the uniformity and repeatability of the sensing gap size defined by the whole wafer bonding process cannot be ignored.

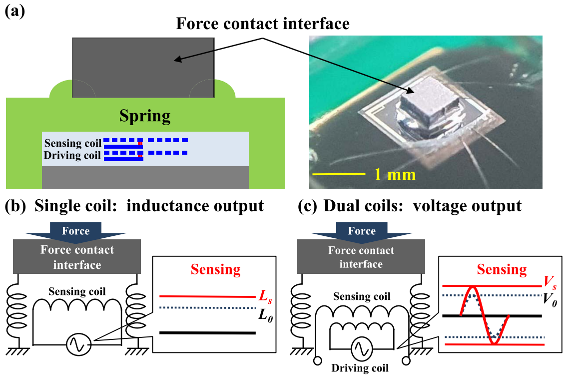

Fig. 16. (a) The schematic illustrations and the micrograph of the CMOS-based inductive tactile force sensor for normal force detection using stainless steel sheet force contact interface (micrograph reprinted from [94], copyright © 2019, Elsevier), (b) single coil signal pick-up for inductive sensing, and (c) dual coils signal pick-up for inductive sensing.

V. INDUCTIVE

As compared with the piezoresistive and capacitive MEMS sensors, inductive sensors are found in fewer commercial MEMS products (e.g. fluxgate magnetometer using the magnetic induction sensing mechanism [85], [86]), which is due to the process development and integration of customized magnetic film (e.g. strong magnetic field inside the process equipment). Nevertheless, many research investigations regarding the inductive MEMS sensor are continuously being reported, such as the proximity sensor [87], tactile force sensor [88], [89], pressure sensor [90], accelerometer [91], and so on. The sensing signal is mainly introduced by the magnetic flux variation of the coil (or inductor) and can be detected by either the inductance output or the voltage output induced by the electromagnetic induction [92]. Thus, the inductive MEMS sensors are typically equipped with coils to generate magnetic flux, and a movable or deformable medium as well as preferred materials to induce magnetic flux change. In terms of fabrication processes, the electroplating technique is the typical way to implement the micro planar-shaped coil [87]–[89]. However, as limited by the process capability, a relatively large device is required to fulfill the coil number design. In this regard, the CMOS process (as depicted in Fig. 1) with the available functional material (metal) is a promising option to implement the sensing coil for inductive sensors. The fine linewidth/pitch and multiple metal layers processes enable the size reduction of the sensing coil [93] as well as of the inductive tactile sensor. Moreover, when applying the tactile load, the methods to induce and pick-up magnetic flux variation of the sensing coil are also important design considerations [94]. The existing articles mainly employ the CMOS technology to fabricate coils and sensing circuits, and then further integrate deformable and signal pick-up structures on chip [94]. The force contact interface mentioned in Section 3 plays a more important role here.

As shown in Fig. 16a, the CMOS chip (TSMC 0.35 μm 2P4M standard CMOS process) with coils is encapsulated by polymer (molding process) and then bonded with the stainless steel sheet (laser-cut process) to form the inductive 1-axis tactile sensor [94]. The flexible polymer acts as the deformable spring, and the rigid stainless steel sheet serves as the force contact interface as well as the medium to interact with magnetic flux (magnetic bump). In Fig. 16b and Fig. 16c, the equivalent electrical-mechanical model (including magnetic bump, mechanical spring, and the sensing coil with AC input) is shown. When applying normal tactile force, the polymer would deform, causing the stainless steel sheet to approach the coils, which leads to magnetic flux change. Thus, the tactile normal force is detected by the magnetic flux variation (ΔL, from L_0 to L_S). Since four metal layers are available in this CMOS process, two coils can be vertically integrated in the chip. Thus, the CMOS chip offers two magnetic flux pick-up methods based on single coil or dual coils designs, as shown in Fig. 16b [94]. For single coil design, the coil (sensing coil in Fig. 16a) will generate, as well as pick-up, the magnetic flux to detect the inductance change. For dual coils design (as shown in Fig. 16a), the input signal is applied to the driving coil and the output voltage change signal (ΔV, from V_0 to V_s) is pick-up by the sensing coil. Note that the sensing performances can be easily modulated by using different polymers and different sizes of the stainless steel sheets.

The sensing architecture in Fig. 16 can be extended to different designs. As shown in Fig. 17a, the force contact interface is replaced by the commercially available chrome steel ball [95], [96]. Moreover, as displayed in Fig. 17b, two distinct force contact interfaces (chrome steel ball and magnetic polymer composite (MPC)) are respectively integrated with the polymer encapsulated CMOS chip by using the wafer-level silicon molding process [97]. Thus, the characteristics of inductive sensors can be modified by changing the polymer materials (acting as spring in these designs) and the changing of photo masks is not required. Furthermore, the tri-axial tactile forces sensing can be achieved by changing the coil design. As shown in Fig. 18a, sensing coils on CMOS chip become the 2 × 2 array design [98]. The in-plane and out-of-plane forces will cause the deformations of polymer, and respectively lead to the gap and overlap-area change between stainless steel sheet and coil array. Thus, tri-axes tactile forces are detected by signals from four coils. Furthermore, the above concept can be applied to the application of micro joystick by changing the design of force contact interfaces [99], as depicted in Fig. 18b. The stainless steel sheet with

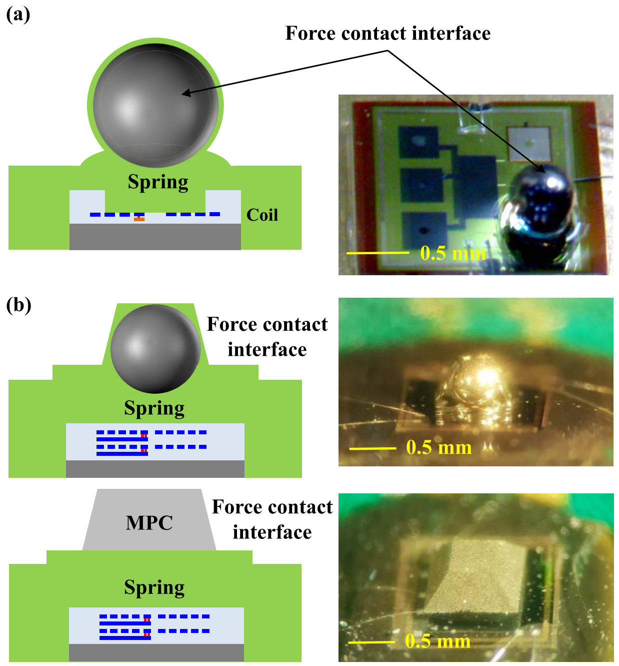

Fig. 17. Schematic illustrations and micrographs of the CMOS-based inductive tactile force sensor for normal force detection using different force contact interface designs, (a) chrome steel ball (micrograph reprinted from [95], copyright © 2018, IOP Publishing), and (b) the encapsulated chrome steel ball and magnetic polymer composite (MPC) through polymer molding (micrograph reprinted from [97], copyright © 2019, IEEE).

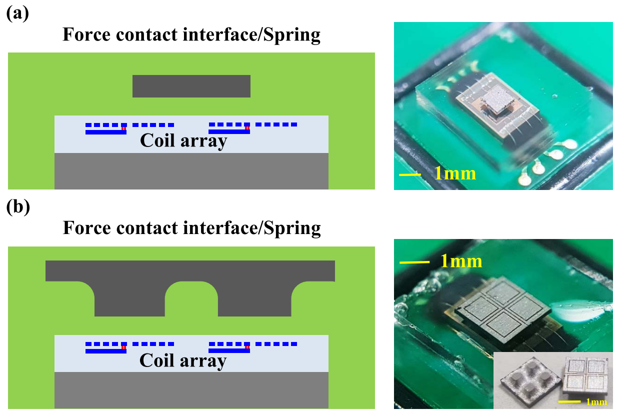

Fig. 18. Schematic illustrations and micrographs of the CMOS-based inductive tactile force sensors, (a) for tri-axial force detection using stainless steel sheet force contact interface (micrograph reprinted from [98], copyright © 2019, IEEE), and (b) for micro joystick application using 3D etched stainless steel sheet force contact interface (micrograph reprinted from [99], copyright © 2019, IEEE).

bumps is fabricated by the commercially available etching and laser cutting processes.

To shrink the size of the sensor, a flip bonded backside loading design is presented in [100], as shown in Fig. 19. A cavity is defined on the backside of the CMOS chip with inductive sensing coil to house the polymer filler as spring and chrome steel ball (force contact interface). Thus, the additional mold for polymer filling in [94]–[99] is not required, and the detaching of the assembled ball by shear loads could be avoided [95], [96]. This design also shows the capability of monolithically integrating the resistive temperature detector (RTD) on the CMOS chip to *in-situ* monitor the temperature of the contact object, and the thermal drift of sensing signals can also be compensated.

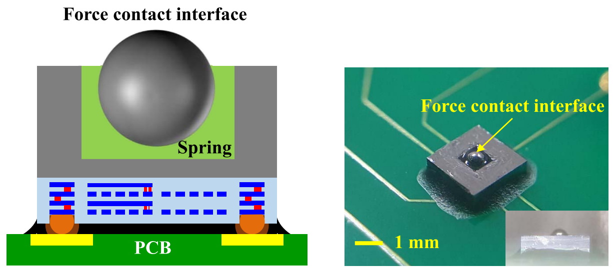

Fig. 19. The scheme illustration and the micrograph of the CMOS-based inductive tactile force sensor for normal load/temperature detection using flip-chip design (micrograph reprinted from [100], copyright © 2020, IEEE).

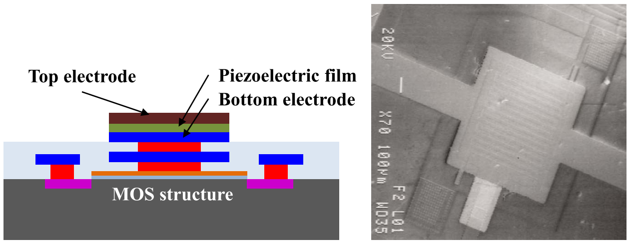

Fig. 20. The schematic illustration and SEM micrograph of the CMOS-based piezoelectric tactile force sensor for normal dynamic force detection (SEM micrograph reprinted from [109], copyright © 2009, AIP Publishing).

In conclusion, magnetic sensing is a promising approach for the development of various sensors. However, the chip scale MEMS magnetic sensors are limited by the fabrication and integration of thin magnetic film. This section reviews the approaches to fabricate coils using the standard CMOS process, and further implement the CMOS-based inductive tactile sensors [94]–[100]. The deformable structures are mainly contributed by the molded polymer instead of the suspended CMOS layers in Sections 3-4. Thus, the problems resulted from the residual stress and CTE mismatch of CMOS layers can be avoided. Through the design and integration of coils and force contact interface (magnetic bump), various inductive tactile force sensor (e.g. 1-axis to 3-axis force sensors) for different applications can be achieved. Moreover, multiple coils can be realized through the available metal layers of CMOS processes to offer different sensing mechanisms. As a result, by using the polymer molding and metal assembly processes on the CMOS chip, inductive tactile force sensors can be easily achieved. Note that the inductive tactile sensors reviewed in this section exploit the assembly approach to integrate magnetic bump as the sensing interface, hence the process to prepare the magnetic film is not required. Nevertheless, the inductive sensors reviewed in this section employed the molded polymer as the spring, and hence their performances (e.g. sensitivity, initial offset, etc.) are sensitive to the fluctuation of ambient temperature [94]–[100]. The monolithically integrated thermometer on the CMOS chip could help to *in-situ* monitor the ambient temperature for signal compensation.

VI. PIEZOELECTRIC

The bulk piezoelectric materials have been applied in many commercial transducers [101], [102]. According to the progress of process technologies, the applications of thin film piezoelectric materials have remarkably increased recently. For instance, the piezoelectric sensing mechanism is exploited

TABLE I

CMOS AND POST-CMOS PROCESSES FOR CMOS-BASED TACTILE SENSORS IN THIS REVIEW

CMOS process	*Post-CMOS processes*
● Austriamicrosystems 0.8 μm 2P2M CMOS process ● Austriamicrosystems 0.6 μm 3M CMOS process ● X-FAB Semiconductor Foundries 0.6 μm 2P3M ● Micronas 0.45 μm CMOS process ● Jazz Semiconductor 0.35 μm BiCMOS process ● KEC Corporation 1.5 μm SOI CMOS process ● TSMC 0.35 μm 2P4M CMOS process ● TSMC 0.18 μm 1P6M CMOS process ● In-house NMOS/CMOS process	● Surface micromachining ● Bulk silicon etching ● Electroplating ● Poling treatment (Piezoelectric sensing) ● Polymer dispensing, gluing, or molding ● Force contact interface integration ● Wire bonding/Flip chip bonding ● MEMS/CMOS chip integration (two chips solution)

TABLE II

CMOS-BASED TACTILE SENSORS WITH DIFFERENT TRANSDUCTION METHODS AND THEIR BENEFITS/CONCERNS

Transduction methods	***Benefits***	***Design concerns***	***Process concerns***
Piezoresistive	● Simple signal processing ● Compatible with various structure designs (easily to embed the piezoresistors in the CMOS process) ● Relatively compact sensing unit as compared with other transduction methods	● Thermal influences (material, etc.) ● Suspended thin film structures (residual stress of CMOS films) ● Relatively high power consumption	● Selectivity of the etchant in releasing process ● Piezoresistivity control of CMOS ● Residual stress of CMOS layers ● Thermal budgets of CMOS
Capacitive	● Submicron gap precisely defined using CMOS layers (one chip solution defined in CMOS BEOL process) ● Low power consumption	● Thermal influences (CTE mismatch of the CMOS composite thin films, etc.) ● Suspended thin film structures (residual stress of CMOS films) ● Parasitic capacitance influences in the circuit	One chip solution (membrane through etching): ● Selectivity of the etchant in releasing process ● Residual stress of CMOS layers ● Thermal budgets of CMOS Two chips solution (membrane through bonding): ● The control of the gap between the capacitor ● Dielectric film or stopper to prevent electrical short ● The control of the thickness of the etched silicon ● Thermal budgets of CMOS ● Bonding alignment issues
Inductive	● Thin film structure avoidable ● Simple fabrication processes ● Distinct signal pick-up options	● Thermal influences (expansion of the polymer, etc.) ● Material selection of the magnetic bump spring design ● Relatively high power consumption (same level with piezoresistive type)	● Thickness and uniformity control of the polymer ● Magnetic properties fluctuation by laser machining (magnetic bump) ● Pick-place issues of magnetic bump (e.g. misalignment, etc.)
Piezoelectric	● Thin film structure avoidable ● MOS transistor for sensing and circuit configuration ● Wide dynamics load sensing capability (~1kHz) ● Low power consumption	● Thermal influences (material) ● Sensitive to dynamic load only ● Noise of the bottom piezoresistive signal of the MOS transistor ● Pre-load is a necessity in operation	● Availability and compatibility (thermal budget, poling voltage, etching…) of piezoelectric film in CMOS ● Uniformity of the thickness of the piezoelectric film ● Uniformity strength of the poling process

to detect dynamics loads such as accelerometer [103], microphone [104], piezoelectric micromachined ultrasonic transducers (PMUT) fingerprint sensor [105], and so on. The piezoelectric sensing mechanism is mainly accomplished through the variation of the electrical dipole inside the material under external physical loads [106]. As the piezoelectric film is subjected to external physical loads, it will generate stress and further introduce charges. Thus, the external loads (such as pressure, acceleration, etc.) applied on sensor can be detected through the charge variation. In this regard, as the piezoelectric film is attached to the suspended MEMS structure, the stress as well as charges can be increased [107]. Moreover, the sensor performances can be further enhanced by larger piezoelectric coefficients of the film (e.g. d_{31}, d_{33}) [108]. Though the concept is similar to the piezoresistive type sensors, it is challenging to fabricate and integrate the piezoelectric films and their electrodes. Especially since existing thin films in the standard CMOS processes have no piezoelectric materials. Other issues such as the process conditions (for example: temperature), contamination, and so on, are also critical concerns for the CMOS foundry. Furthermore, due to the characteristic of piezoelectric film, it can only be applied to detect dynamic loads [109]–[112]. In this section, the integration of the piezoelectric film with the CMOS process to implement the tactile force sensors will be discussed [109]–[112].

The integration of the piezoelectric film on top of the NMOS/CMOS chip (in house process in Italian Institute of Technology) to fabricate the Piezoelectric oxide semiconductor field effect transistor (POSFET) for the detection of the tactile normal dynamic force is reported in [109], [110], [111]. As depicted in Fig. 20, after the NMOS/CMOS processes, the piezoelectric polymer film (P(VDF-TrFE)) and the top electrode are then defined on the MOS structure. Note that the poling condition of piezoelectric polymer film (85 °C, 200 V (in four cumulative steps of 50 V each)) is considered in the process to avoid damaging or altering the characteristics of underlying MOS devices. When applying the normal tactile load on sensor, additional charges will be induced in the piezoelectric film, and further transferred to generate the channel current into the MOS transistor for signal detection. The same concept can be extended into the array design to detect the tactile load distribution, and the temperature sensor is integrated during the NMOS/CMOS process to monitor the thermal distribution and calibrate the noise from the pyroelectric noise of the piezoelectric film [112].

Presently, many process technologies have been developed to fabricate piezoelectric films, such as ZnO, AlN, PZT, and so on, with good material properties [108]. Thus, the piezoelectric films can find extensive applications in micro sensors and actuators. Nevertheless, for the application of piezoelectric film on the CMOS platform, the process integration remains a critical concern. This section reviews an article to show a simple approach to integrate the piezoelectric film and the MOS device by using the post-CMOS process. For future applications, through the additional backside Si etching on the device in Fig. 20, the piezoelectric film could be attached to a suspended MEMS structure so as to enhance its sensitivity. Thus, the sensitivity and sensing range of this device can be modulated by the depth of backside Si etching. For real applications, the static tactile load sensing unit is still required on this CMOS chip to ensure the proper contact of the loading object during the dynamic force measurement.

VII. CONCLUSION AND FUTURE OUTLOOK

The standard CMOS platforms together with post-CMOS processes have been extensively applied to implement various micro sensors. Such approaches could leverage the mature CMOS technologies and also offer the capability of monolithic integration of sensing circuits. The available thin film layers in FEOL/BEOL of CMOS processes provide the required functional materials and electrical routings to realize tactile force sensors of piezoresistive, capacitive, and inductive types. The piezoelectric type sensor can also be developed by adding the functional thin film in the post-CMOS processes. In summary, the CMOS-based fabrication processes are a promising approach to implement micro tactile force sensors. This review introduces various CMOS-based tactile force sensors. Table I summarizes the fabrication processes, including the CMOS and post-CMOS processes, employed and developed to realize the tactile force sensors in this review. Among them, the standard CMOS processes available in the commercial foundries are mature and stable, whereas the customized CMOS processes available in IDM (Integrated Device Manufacturer) or research laboratories are flexible. Moreover, most of the post-CMOS processes introduced in this review mainly used thin film layers and silicon substrate etching to fabricate the suspended MEMS structures. The additional photolithography, thin film deposition and patterning, and even bonding processes have also been exploited in some review articles to show the flexibility of the post-CMOS fabrication. In fact, TI and TDK-InvenSense have demonstrated commercial products by adding additional MEMS processes on the CMOS chip [39], [112]. However, if not an IDM, the support from foundries for process development is required.

The article also respectively reviewed tactile sensors of different sensing mechanisms by using the functional materials available in the CMOS processes. As discussed in Section 3, the poly-Si and Si defined in the FEOL CMOS process are used to implement the piezoresistive tactile force sensors. As reviewed in Sections 4 and 5, the metal layers in the BEOL CMOS processes enable the realization of the capacitive and inductive tactile force sensors. Although piezoelectric materials are not available in the CMOS platform, the piezoelectric tactile force sensor can be fabricated through the compatible post-CMOS processes introduced in Section 6. Table II summarizes the advantages, design and process concerns for CMOS-based tactile sensors of different sensing mechanisms in this review. Moreover, as shown in Fig. 1, the commercial tactile sensors generally exploit polymer materials as the force transmission medium or the force contact interface. Thus, for real applications, to use the polymer materials as the force transmission medium or the force contact interface is also a critical design consideration for tactile force sensors. Some of the articles in this review have shown different approaches to add the polymer layer on the CMOS-based sensing chip, and the polymer layer can even be exploited to modulate the performances of the tactile force sensor. However, as reported in [100], the high CTE and low thermal conductivity of polymer material will cause problems for the tactile force sensors. The performances of tactile force sensors are also affected by the characteristics of polymer materials, such as the stress-strain hysteresis, non-linear deformation, viscoelastic behavior, reliabilities, and so on [114]–[124]. It is suggested that the integration and influence of polymer contact interface cannot be ignored while designing the tactile force sensors. Additionally, the processing of the polymer during fabrication of the sensor is also a concern, for example, necessary vacuum operations to prevent air bubbles in the polymer. Table II also summarizes the advantages and design concerns for polymer materials in this review.

This review has summarized various CMOS-based tactile force sensors of different sensing mechanisms. In fact, many different information other than force (for example, temperature, texture, etc.) can also be detected and received through the contact of objects. Thus, the integration of different tactile sensors could offer more contact information to the machine to enhance the human-machine interaction. Moreover, additional sensing device such as proximity sensor can be integrated with tactile sensors for safety concern. The CMOS-MEMS technology has shown its capability for monolithic integration of multiple sensors [39]–[42]. In other words, to achieve the monolithic integrated tactile sensing hub (including force, temperature, proximity, etc.) on a single chip will be another advantage for the CMOS-MEMS technology. In summary, the CMOS-MEMS is a promising technology for the tactile sensing applications.

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